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ABSTRACT

A new method was developed by the Image Permanence Institute for monitoring the effects of dynamic environmental conditions on organic materials in order to make it easier to manage the preservation of library and archives collections. This new approach to preservation management applies to the many types of scholarly resources for which research and academic institutions are responsible. The Time-Weighted Preservation Index (TWPI) provides a new way to measure and quantify how temperature and humidity changes affect the preservation quality of storage environments for paper, photographic, and magnetic tape collections, and any other type of organic material. The concept is illustrated with examples and explanations are given on how relatively small changes in storage conditions can result in significant improvements in the useful life of library and archives collections. Plans for the Preservation Environment Monitor are also described. Appendices provide information on the following: forms of deterioration in organic collection materials, deterioration mechanisms and test methods; specific origins of the preservation index (PI) model and how the PI model compares with other published models; and temperature and RH equilibration in TWPI analysis. (Contains 39 references.) (AEF)

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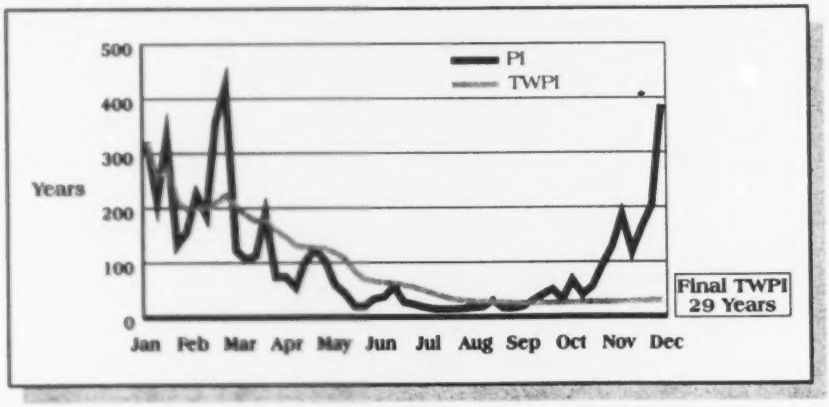
New Tools for Preservation

Assessing Long-Term Environmental Effects on Library and Archives Collections



November 1995

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New Tools for Preservation

Assessing Long-Term Environmental Effects on Library and Archives Collections

by James M. Reilly, Douglas W. Nishimura, and Edward Zinn
Image Permanence Institute
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November 1995

The Preservation Science Council (PSC) of the Commission on Preservation and Access, organized in 1992, is a group of preservation administrators and scientists who seek to understand and define the research needs and key technical problems of information collections. Meetings of the Council during 1992–1994 offered a unique opportunity for the producers and consumers of research to learn from each other. Over the course of three meetings in a retreat-like atmosphere, scientists and preservation administrators winnowed a list of potential project ideas and developed a set of criteria for research projects: 1) they must relate to materials that exist in large quantities and contain information of cultural significance, 2) they must address preservation problems that are serious in the near and middle term, and 3) they must be projects that are practical and achievable given the research resources available to the preservation field.

In early 1994, the Preservation Science Council put forward a list of six high-priority preservation research projects. Interestingly, most of the projects dealt with the theme of understanding and using the storage environment to better advantage. Although the projects dealt with diverse materials and explored different specific goals, the *leitmotif* of the PSC's work was the powerful role of temperature and humidity in advancing or retarding the progress of deterioration. Building on the work of Donald Sebera (see *Isoperms, An Environmental Management Tool*, published by the Commission in June 1994) it became clear that the preservation community could begin to use this relationship in order both to save money and to make collections last longer. The PSC identified an urgent need for more *management tools* by which critical relationships, such as the one between the rate of chemical change and environmental conditions, could be understood and applied in practice. The concepts for long-term environmental assessment offered in this publication represent a continuing trend toward utilization of scientific principles in preservation management.

Author's acknowledgment

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Table of Contents

Introduction 1

Preservation and the Storage Environment 2

Why Aren't We Using Better Storage to Achieve Institutional Preservation Goals? 3

A New Approach to Environment Assessment and Control 4
- **Preservation Index: A New Measure of the Storage Environment** 4
- **Time-Weighted Preservation Index: A Cumulative Measurement Over Time** 5

How to Use PI/TWPI 5
- **PI Values** 5
- **The Principles Behind TWPI** 7
- **PI/TWPI Analysis as a Management Tool in Preservation** 9
- **An Example of TWPI in Practice** 10
- **Useful Insights from TWPI** 14

The Preservation Environment Monitor 14
- **Guidelines for Application of PEM** 17
- **The PEM as a Survey Tool** 17

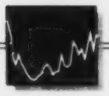
Appendix I 19
- **Forms of Deterioration in Organic Collection Materials** 19
  - Pollutant-Induced Deterioration 19
  - Light-Induced Deterioration 19
  - Biological Deterioration 19
  - Physical Deterioration 19

Appendix II 21
- **Technical Basis for the PI Concept: Background on Deterioration Mechanisms and Test Methods** 21
- **Arrhenius Testing: Reaction Rate Determinations from Accelerated-Aging Studies** 21
- **Activation Energy: Temperature's Influence on Reaction Rate** 23
- **Table of Published Activation Energies** 24
- **"Intercept": Predicted Life at Room Temperature** 24
- **Can We Trust Accelerated Aging?** 24

Appendix III 27
- **Technical Basis for the PI Concept: Specific Origins of the Preservation Index Model** 27
  - Activation Energy/Temperature Dependence 27
  - Time Values Chosen for the PI Model 27
  - RH Effects in the PI Model 28
  - IPI Acetate Film Data Used To Define PI Data Set 28
- **How the PI Model Compares with Other Published Models** 28

Appendix IV 30
- **Temperature and RH Equilibration in TWPI Analysis** 30
  - Compensating for Differences in Temperature and RH Equilibration Rates 31
  - Temperature Equilibration Lag Time 31
  - RH Equilibration Lag Time 32

References 33



Introduction

In this publication, the Image Permanence Institute introduces new concepts and a new electronic instrument for environmental monitoring. The purpose is to make it easier to manage the preservation of library and archives collections by revealing the long-term effects of storage environments on the deterioration of organic materials. Awareness of environmental effects is the basis for a program of cost-effective improvements.

IPI's new methods are being developed with funding from the Division of Preservation and Access of the National Endowment for the Humanities. These ideas represent a further evolution of the philosophy embodied in Donald Sebera's *Isoperms, An Environmental Management Tool*.[1] The approach is like *Isoperms* in some ways, but it differs in some important respects. It measures the combined effect of temperature and relative humidity on the "preservation quality" of a storage environment, but it is a *general measure*—one that applies to all organic materials, not just to paper. Perhaps the most important difference is that it is now possible to measure the preservation quality of *dynamic environments*, allowing a whole period of changing conditions to be characterized in a single value: the Time-Weighted Preservation Index (TWPI). TWPI offers new kinds of insights into environmental trends. It is a key enabling technology for cost/benefit analysis in library and archives preservation. TWPI analysis can be helpful to preservation managers in several ways:

- TWPI analysis boils reams of environmental data down into one easily grasped "bottom-line" figure.
- TWPI quantifies the preservation quality of a storage environment and can be used to document the value of environmental improvements to administrators, to compare one storage area with another, and to benchmark institutional performance against that of other libraries and archives.
- Graphs of TWPI versus time can highlight the times of year or the particular conditions that are most damaging to collection materials.
- TWPI gives immediate feedback on the results of relatively modest incremental improvements such as reducing thermostat settings and pulling window blinds.
- Using simulated temperature and RH data, TWPI analysis can estimate the effects of *potential* improvements in storage conditions. Preservation personnel can know beforehand how much might be gained through large or small improvements and weigh them against their cost.

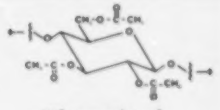
IPI's NEH-sponsored project is aimed at developing the TWPI concept into a practical tool for everyday use. Specifically, IPI is developing and testing the Preservation Environment Monitor (PEM), a battery-powered device that does the work of a hygrothermograph and a datalogger, and also displays TWPI (the "bottom line") in real time. The PEM will provide more accurate temperature and RH measurements than existing devices and will make it much easier for institutions to know how good or bad (in terms of slow deterioration of the collections) their storage environment really is. Armed with TWPI information, institutions will find that, in many cases, significant improvements in the useful life of their collections can be accomplished by relatively modest incremental changes in storage locations and HVAC setpoints.

In the sections that follow, IPI introduces the TWPI concept and offers some examples of its use. Plans for the Preservation Environment Monitor also are described. The Commission and the authors invite your comments and suggestions.

Preservation and the Storage Environment

A central challenge in preservation is to extend the useful life of collection materials. Given the current reality of increasing demand for access to collections—even as funding is static or shrinking overall—the problem is simply to do more preservation for the same or less money. Moreover, it is often not enough just to understand how to improve the care of collections; the benefits of preservation actions now must be communicated to administrators and somehow quantified in order to lay claim to scarce institutional resources. This has been a source of great difficulty for preservation managers, because much of their work is preventive rather than remedial in nature. As such, it is intangible and difficult to quantify in terms of dollars and cents or years of extended life.[2,5]

Both basic science and actual experience agree that temperature and RH are the primary rate-controlling factors in chemical decay, mechanical damage, and biodeterioration, as well as other forms of deterioration. Every treatise on preservation and conservation advises that cooler and (within limits) drier conditions are better for the collections. Moreover, the major preservation problems that now occupy so much of our efforts—brittle books,[4] degrading nitrate and acetate film base,[5,6] color dye fading, audio and video tape deterioration[7]—are due to *chemical* changes that are influenced heavily by storage temperature and RH. In fact, all organic materials in collections—from natural history specimens to leather bindings, grass baskets, textiles, and on and on—deteriorate because of chemical reactions that go faster or slower according to storage temperature and RH.[8,9] (For more information on the other forms of deterioration affecting collections, see **Appendix 1**.)

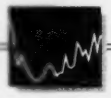


Chemical Deterioration

Inherent chemical deterioration in organic materials is an ever-present threat because it is the material itself that undergoes the reactions of decay—neither external pollutants nor exposure to light are required. We can shield collections from pollutants and keep them in the dark, but some level of thermal energy and some moisture are always present, and these are the environmental factors that govern the rate of chemical deterioration. Examples of chemical deterioration are the discoloration and embrittlement of paper and the fading of dyes in color photographs. Paper becomes brittle through a long process of chemical changes on the molecular level (specifically through chain scission in cellulose molecules). The rate of attack on the cellulose linkages varies over time, depending on the temperature and the moisture content of the paper. If enough linkages are broken, brittleness results. Although the ultimate manifestation of deterioration (the brittleness) is a physical property, the underlying cause is a chemical process, and its rate is governed by temperature and RH in the storage environment. Higher temperatures cause molecules to move faster, collide more, and react more rapidly with each other. With higher humidity, more water is available for hydrolysis reactions. Thus, paper embrittlement, dye fading, leather rot, "sticky shed" syndrome in magnetic tape, loss of strength in textiles, and a host of other important forms of decay in organic materials are regarded as manifestations of underlying chemical deterioration processes.

Over the last twenty years—and especially within the last five years—a great deal of laboratory work has been done to establish predictive models of deterioration for important materials such as paper,[10,11,12] magnetic tape,[7,13,14] and photographic film.[5,6,15,16] These models, perhaps the best-known being the "isoperm" approach of Donald Sebera (formerly at the Library of Congress),[1,17] have shown just how long even inherently unstable materials can last under the right storage conditions. They also show the converse—that the wrong environment can doom collections to very short lifetimes.

Although the weight of evidence and opinion is firmly behind the importance of regulating the storage environment, there is still some way to go before the everyday practice of preservation management makes full use of scientific principles in regulating library and archives storage conditions. The necessity for RH control to avoid mechanical damage or mold growth is fairly well understood, and efforts are made to apply this knowledge in practice. However, the magnitude of the effect of temperature and RH on the rate of *purely chemical forms of deterioration* is not widely known or appreciated, nor is it used in everyday practice. Despite the availability of sophisticated technology for temperature and humidity measurement, the preservation field still lacks a practical means to measure and quantify how RH and temperature act together to affect "chemical lifetime," particularly when the environment is changing from day to day or season to season.

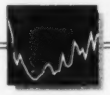


Why Aren't We Using Better Storage to Achieve Institutional Preservation Goals?

There are two principal reasons why we are not using better storage to achieve institutional preservation goals. First, collection personnel have very little long-term information about the storage environment because the available means to collect that information—hygrothermographs and dataloggers—are costly and cumbersome. The technology of environmental monitoring often is the domain of building engineers, not library or archives staff. Second, and more important, interpreting temperature and RH data is complex and beyond the ability of all but a few specialists. Most people's idea of a good storage environment is one that is comfortable for them and has no RH fluctuations. Such an "analysis" completely misses the point of how the storage environment acts to speed up or slow down the rate of decay in collection materials. In fairness, people don't have time to become experts in mechanisms of chemical and mechanical damage, nor should they. Ways must be found to deliver sophisticated "bottom-line" judgments to collection personnel without their having to become experts themselves. One needn't become a meteorologist to understand the weather forecast. Managers and staff in libraries and archives need a basis for evaluating long-term environmental effects in order to influence decisions made by physical plant directors and higher-level administrators. The ability to quantify the impact of existing or planned storage circumstances on the useful lifetime of collections is a vital element in discussions about building renovations, HVAC installations or upgrades, system failures, weekend shutdowns, and system setpoints.

IPI's new environmental monitoring technology will make it much easier to collect information about storage environments and to immediately assess environmental effects on collection materials. Currently available instruments present many practical difficulties.[18] Hygrothermographs can be intimidating. They are labor-intensive (charts must be changed on a weekly or monthly basis, with recalibration required every few months) and they give only a snapshot of storage conditions; creating long-term data means hours of replotting or keyboarding data. An electronic datalogger makes it easier to obtain long-term data, but it can be more intimidating than a hygrothermograph. Dataloggers are complex devices that require a fairly high degree of computer expertise to use. They have no displays and thus offer no feedback, except to those who can master their accompanying software. Neither dataloggers nor hygrothermographs are user-friendly tools for librarians and archivists, who don't have the time, or for that matter, the motivation, to learn to use them.

Long-term data are required for evaluating the danger posed by all the principal forms of deterioration influenced by temperature and RH. (We will demonstrate in this publication how long-term environmental trends determine chemical lifetime.) On the other hand, biological forms of deterioration and mechanical damage from RH changes are popularly believed to be relatively short-term phenomena that can happen without warning. Although in special circumstances mechanical/structural problems and biological attack can occur quickly, more typically they are related to circumstances that develop over months and years.[19,20] For example, many cases of severe mechanical damage happen when objects have become equilibrated to high RH over a long time, and then are brought quickly into dry circumstances.



A New Approach to Environment Assessment and Control

Although obtaining temperature and RH data is difficult, *interpreting* it is even more challenging. Extracting an overview of how rapidly deterioration is progressing from a large table of RH and temperature data, or from a series of hygrothermograph charts, is extremely difficult. It would be easier to estimate the Dow Jones averages from watching the ticker of individual stock trades. The TWPI approach to environmental assessment represents a wholly new quantitative approach to monitoring, evaluating, and regulating the collection storage environment. The purpose of TWPI is to simplify the interpretation of temperature and humidity data. TWPI analysis is relevant to the preservation of all *organic* materials—this includes most objects in libraries, archives, historical collections, museums, natural history collections, and ethnographic and archaeological collections. (It does not directly apply to inorganic objects, such as stone or metals, because the forms of deterioration that afflict them, while often chemical in nature, do not have a strong temperature dependence.) The new approach centers on two new measurements:

- The Preservation Index (PI), for evaluating the effect of particular combinations of static and unchanging temperature and RH conditions on the rate of chemical deterioration in collections.

- The Time-Weighted Preservation Index (TWPI), for evaluating the total cumulative effect, over time, of changing temperature and RH conditions on the rate of chemical deterioration in collections.

Preservation Index: A New Measure of the Storage Environment

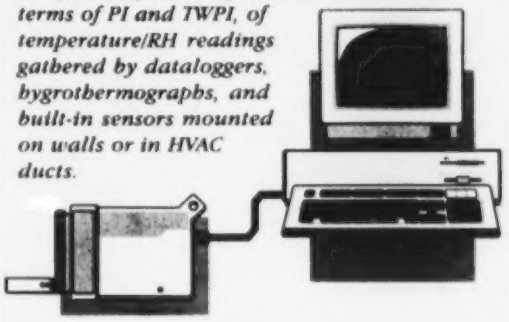
The Preservation Index is a means of expressing how ambient temperature and RH affect the chemical decay rate of collections. PI has units of years and gives a general idea of how long it would take for vulnerable organic materials such as poor-quality paper to become noticeably deteriorated, assuming that the temperature and RH did not change from the time of measurement onward. PI helps us to quantify how good or bad the environmental conditions are at that moment for chemical deterioration of the collection. The "years of life" aspect of PI values was chosen deliberately to reflect the behavior of relatively short-lived materials. PI is *not* meant as a predictor of the useful life of any particular object. It is simply a convenient measure of the effect of current environmental conditions on the overall life expectancy of the collection, using shorter-lived materials as a yardstick.

Time-Weighted Preservation Index: A Cumulative Measurement Over Time

Two Paths to TWPI Analysis

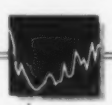
1. Devices (such as IPI's Preservation Environment Monitor) that sense temperature and RH, then calculate and display temperature, RH, PI, and TWPI in real time.

2. After-the-fact computerized analysis, in terms of PI and TWPI, of temperature/RH readings gathered by dataloggers, hygrothermographs, and built-in sensors mounted on walls or in HVAC ducts.



Nearly every storage environment is dynamic, changing with the weather, with the seasons, or by conscious actions taken to save money or to be more comfortable. It is difficult enough to know the effect of any given *static* condition on the decay rate of a collection; the total effect of *changing* conditions over time has been impossible to obtain at all, until now. The TWPI makes it possible to measure the effects, not of just one set of conditions, *but of fluctuating conditions, over a whole period of time, expressed as a single value.*

TWPI is an average of changing PI values over time. If PI values are obtained at regular time intervals, a relatively simple recursive calculation (one that is repeated again and again with new data) can produce a single number that accurately expresses the average rate of deterioration for the time period. This number is the TWPI. It represents the approximate amount of time, in years, that vulnerable organic materials would last if every time period in the future were just like the one during which the TWPI value was measured. TWPI values can represent the cumulative effect of a week's, a month's, or several years' worth of temperature and RH conditions. As the bottom-line summary of the preservation quality of a storage environment, TWPI is far more meaningful than any other single piece of data—it is what collection managers really want to know about their storage areas. The **Appendices** discuss in detail the specific origins of the PI values as well as a number of technical issues concerning this generalized model, such as accounting for differences among materials, the reliability of accelerated aging, and other forms of deterioration.



How to Use PI/TWPI

PI Values

Preservation Index is a convenient way to measure and talk about the effect the storage environment has on inherently problematic materials such as acidic paper, color photographs, magnetic tapes, and binding adhesives. Underlying the PI concept is the assumption that temperature and RH act together to speed up or slow down chemical deterioration to more or less the same degree in all organic materials. This assumption is, of course, not strictly true (there is still a need to investigate specific materials on their own), but for the purposes of making judgments about storage condi-

tions for mixed collections, it is close enough. The PI model also assumes that materials of special interest for preservation managers are those that become noticeably deteriorated in less than 50 years at average room conditions. This reflects the approximate lifetime of unstable materials (see **Appendix III** for more details). Although it is based upon the behavior of inherently short-lived materials, PI is useful in a relative way for inherently long-lived materials, too. If the PI were doubled, long-lived materials like rag paper would chemically degrade only half as quickly and would likely last twice as long.

PI values represent the approximate amount of time that an inherently unstable organic material, such as magnetic tape binder or a color slide, would last at any combination of temperature and RH. How long the material lasts in this sense is the time required to become noticeably deteriorated, although not necessarily completely unusable. To say that the storage condition of 57°F, 50% RH has a PI of 95 years means that such a material could be expected to degrade in about 95 years if kept constantly at 57°F, 50% RH *for the whole time*. (The effect of varying storage conditions on life expectancy of collections is addressed by TWPI.) At very cold and dry conditions, PI values are high; at warm and humid conditions, PI values are low.

To determine the PI for a given combination of temperature and RH, one simply looks it up in the PI definition table. A selected subset of the large PI definition table is shown in **Table I**. The PI definition table has temperatures along the top and relative humidities along the side. In the main body of the table are the PI values themselves, each one occurring at the intersection of a particular temperature and RH. The full table is quite large, because PI is defined for temperatures from -40°F (-40°C) to 150°F (66°C) and RHs from 5% to 95% (RH values below 5% and above 95% should be treated as 5% and 95% for lookup purposes). The full PI definition table comprises 191 rows and 91 columns and contains PI values for a total of 17,381 different combinations of temperature and RH. Only in rare circumstances would anyone need the low and high extremes in the PI definition table (although such conditions are occasionally reached for a brief period in some areas of the world, and, if the extremes were not represented in the PI definition table, it would be impossible to calculate a TWPI for those storage environments). In fact, the full PI definition table really is needed only when TWPI values are calculated on a computer. To actually make use of PI values in planning a new storage environment, consulting the subset given in **Table I** will likely be sufficient for most purposes.

By itself, the table of PI values is useful for illustrating the tremendous impact of cool and dry conditions on the life expectancy of inherently unstable collection materials. Examination of **Table I** also will show that a number of different temperature and RH combinations will yield the same PI value. This is one of the most important lessons to be learned from modern scientific thinking about preservation. Equivalent permanence can be achieved in a number of different ways; some conditions, however, may cost less than others. The goal of extending useful life at lowest cost is much easier to attain when we can trade off temperature and humidity to maximum advantage.

Chemical decay is the gravest threat to library and archives collections, and therefore PI is a good indication of the overall "preservation quality" of a storage environment. Of course, it is still important to consider all the other possible forms of environment-related decay such as mold growth and pollution. ***PI is meant to supplement, not replace, consideration of these other important environmental issues***. It is always necessary for preservation managers to understand the nature of their collection materials, to assess the seriousness of the threat posed by all the possible forms of decay, and to gather data about actual storage conditions so that appropriate actions can be taken to extend the useful life of the collection.

Table I. Definition table of PI values showing predicted lifetime, in years, of short-lived organic materials at various combinations of temperature and RH conditions. Selected subset of full definition table.

		Temperature (°F)												
		32	37	42	47	52	57	62	67	72	77	82	87	92
% RH	5	2634	1731	1147	767	516	350	240	165	114	80	56	40	28
	10	2234	1473	979	656	443	302	207	143	99	70	49	35	25
	15	1897	1255	837	562	381	260	179	124	86	61	43	30	22
	20	1613	1070	716	482	328	224	155	107	75	53	37	27	19
	25	1373	914	613	414	282	194	134	93	65	46	33	23	17
	30	1170	781	525	356	243	168	116	81	57	40	29	21	15
	35	998	668	451	307	210	145	101	71	50	35	25	18	13
	40	852	572	387	264	182	126	88	62	43	31	22	16	12
	45	729	491	333	228	157	109	76	54	38	27	19	14	10
	50	624	421	287	197	136	95	66	47	33	24	17	12	9
	55	535	362	247	170	118	82	58	41	29	21	15	11	8
	60	459	312	213	147	102	72	51	36	26	18	13	10	7
	65	394	269	184	128	89	62	44	31	22	16	12	9	6
	70	339	232	160	111	77	54	39	28	20	14	10	8	6
	75	292	200	138	96	67	48	34	24	17	13	9	7	5
	80	251	173	120	84	59	42	30	21	15	11	8	6	4
	85	217	150	104	73	51	36	26	19	14	10	7	5	4
	90	187	130	90	63	45	32	23	16	12	9	6	5	3
	95	162	112	79	55	39	28	20	15	11	8	6	4	3
		PI Values, in Years												

The Principles Behind TWPI

If the temperature and RH for a storage area were always the same, PI would tell us all we need to know about the rate of chemical decay for collections stored there. Storage environments in the real world, however, are seldom static. Most storage environments vary with the seasons, weather patterns, diurnal changes, or because of setpoint changes and breakdowns. The patterns of variation may be regular or irregular. How can all this unpredictable change be averaged into a single measurement? What is needed is a way to average PI values over the course of a week, a month, a year, or any desired interval of time, in order to practically evaluate a storage environment. (It should be noted that, because chemical deterioration is a slow, long-term process, the overall average for a year will provide a collection manager with much more meaningful information than only a week's worth of data.)

There is a problem, however, in simply averaging PI values. Depending on how much conditions vary, a week in the summer might have a quite different impact on overall life expectancy than a week in the winter. (Deterioration progresses faster when conditions are warm and humid than when they are cold and dry.) A simple average obtained by adding the PI values for each time interval and then dividing by the number of intervals would be incorrect. Since more deterioration would occur during the week in the summer, to correctly weight each period of time that comprises the average, the fact must be taken into account that *time spent at bad conditions shortens the life expectancy of the collection much more than time spent at good conditions.*

It may seem obvious, but it is worth stating that the nature of chemical deterioration is such that the collection has only "one life to live;" in other words, *deterioration is irreversible.* The rate of progress toward a deteriorated state may be slower or faster at times, but it can never go backward. If we put a brand-new collection into a very cold and dry storage environment where its life expectancy (PI) is 2000 years, its rate of deterioration would slow down tremendously, but the collection nevertheless would continue to deteriorate at some finite rate. When the collection is brought out of the cold environment to a much warmer one, its rate of deterioration would increase, and its life expectancy would be much shorter—only 50 years, for example. What would be the collection's life expectancy if it spent six months of every year in the cold environment and six months in the warm environment?

To answer this question, Mark McCormick-Goodhart[21] of the Smithsonian Institution's Conservation Analytical Laboratory explored the issue of average life expectancy and demonstrated how to compute it correctly. (His conceptual approach to averaging life expectancies also is employed in computing TWPI.) If our collection spent half of every year in the cold environment and half in the warm environment, the simple average (2000 years + 50 years ÷ 2) would predict the life expectancy to be 1025 years. But this cannot be correct. In the warm environment, it would take only 50 years for the collection to deteriorate. If the collection were to spend half of every year in the warm environment, its 50 years of expected life would elapse after 100 years; its "one life to live" would be over. The correct answer is much closer to 100 years than 1025 years.

McCormick-Goodhart's approach is to average the *reciprocals* of life expectancy, not the life expectancy values themselves. This method makes the calculations a little more complex, but it gives us the right answer. The reciprocal of a number is simply 1 divided by the number. In our example, we would first take the reciprocal of 2000 years (1/2000, or 0.0005) and the reciprocal of 50 years (1/50, or 0.02), and then average those values in the normal way. Thus, we add 0.0005 + 0.02 to get 0.0205 and then divide by 2 to obtain 0.01025.

This answer does not seem correct either, but that is because there is one last step. By using reciprocals to obtain the average, what we effectively did was to average together fractional portions of the collection's "one" lifetime. The answer—0.01025—represents the fraction of the collection's one lifetime that would be used up during every year of *combined* six-months-cold, six-months-warm storage. If we wish to get back to what the collection's *overall* life expectancy would be with this kind of storage pattern, the last step must be to take the reciprocal of 0.01025, which is 1/0.01025, or 97.6 years. Note that this, the true answer, is only slightly less than the 100 years the collection would have lasted if deterioration occurred *only* at the warm conditions. While nearly all the deterioration occurs when the collection is in the warm environment and very little occurs during the six months in the cold environment, still enough deterioration goes on in the cold environment to reduce to 97.6 years what otherwise would have been a 100-year overall life expectancy.

This example deals with a simple case that analyzes the effect on overall life expectancy of time spent at only two different storage conditions, but it illustrates the principles behind TWPI. The problem of averaging PI values over time is handled in the same fashion, except that instead of only two intervals being averaged, any number of time intervals of any length can be used. Douglas Nishimura of the IPI staff has worked out a relatively simple formula for calculating TWPI recursively, which means that, after data for each new interval of time become available, the average is updated without having to store and sum the data for all the previous intervals. If all the intervals are of equal length, TWPI may be calculated as follows:

$$TWPI_n = \frac{nTWPI_{n-1}PI_n}{PI_n(n-1) + TWPI_{n-1}}$$

Where:

n = total number of time intervals
$TWPI_{n-1}$ = TWPI after time interval n-1
PI_n = PI measured at time interval n

TWPI is the only way to evaluate the overall impact that changing temperature and RH conditions have on the chemical lifetime of organic materials in collections. In practice, TWPI values must be calculated on a computer. To arrive at the TWPI for a storage area, it is necessary to obtain temperature and RH readings at equal-length intervals over a period of time. (There is a somewhat more complex TWPI formula that can deal with unequal time intervals, but it is rarely needed in practice.) It is then necessary to adjust the temperature and RH readings to compensate for the fact that objects in collections do not immediately equilibrate to changes in room conditions. This is discussed in detail in **Appendix IV**. Next, PI values for each interval must be determined from the PI definition table and then substituted into the TWPI formula above. For the first interval, the PI and TWPI are the same. At the second and each succeeding interval, the calculation is repeated, substituting the appropriate values for the current PI, number of intervals, and TWPI associated with the immediately preceding interval. This process can be repeated as many times as desired, obtaining a TWPI that is the true average for the entire time period.

PI/TWPI Analysis as a Management Tool in Preservation

The ability to compress huge amounts of temperature/RH data into a simple graphical overview (or even to just one number, the final TWPI) is one of the most powerful aspects of PI/TWPI analysis. As a preservation management tool, it is very convenient to deal with a table of weekly, monthly, or annual TWPI values to make sure that collection storage environments are under control and performing as they should. **Table II** shows an example of this kind of management tool. It lists final TWPIs for a one-year period for 17 different storage areas, together with maximum/minimum PI values and the range of PI values at each area.

A summary table like this is far easier to digest and tells much more about chemical deterioration rate than either graphs or tables of raw temperature and RH values. With a glance at the TWPI column, the best and worst environments can be determined. By looking at the column showing the range of PI values (the difference between highest and lowest values measured), it is easy to see which areas have steady conditions and which do not. When the range of PI values measured over a period of time is large, it means that conditions (considered from the point of view of chemical deterioration) have changed during the time period. When the range is small, it means they are steady.

In practice, such a summary table could be produced by a building-wide HVAC system computer that receives input from fixed temperature and RH sensors in ducts, mounted on walls, or elsewhere, and then computes the PI and TWPI values and prints a

Table II. Sample summary of final TWPIs for a one-year period in 17 institutional storage areas. (All values in years.)

Location	TWPI	Max PI	Min PI	PI Range
Geology Library—Director's Office	61	86	53	33
Geology Library—Upstairs, Map Storage Area	38	95	26	68
Main Library—Room A	31	45	22	23
Main Library—Room B, Abandoned Area	30	39	21	18
Undergraduate Library—Room C	49	65	40	25
Undergraduate Library—Room D	51	78	39	39
Undergraduate Library—Basement	57	73	46	27
Main Library—Office Storeroom	32	35	27	8
Main Library—Stacks	44	56	37	20
Main Library—Basement, Area A	46	49	43	6
Main Library—Stacks	42	56	36	20
Main Library—Stacks, Level 5	68	99	60	39
Main Library—Basement, Area B	62	74	57	17
Main Library—Stacks, Level 5	63	77	56	22
Building 2—Auxiliary Storage	51	77	37	40
Geology Library—Basement	49	64	36	29
Serials Holding Area	34	46	28	18

summary table for distribution to preservation managers and building operating engineers. It also could be generated simply by going around once a week or month and writing down the TWPI displayed on a number of PEMs located throughout a building or storage area. Or it could be generated on a computer into which PEM-stored data or datalogger records are uploaded and printed out.

An Example of TWPI in Practice

The real value of TWPI analysis is that it can provide insights into storage environments that are not obtainable any other way. Consider three hypothetical storage areas, which for convenience we will call the "attic," the "closet," and the "basement." The temperature and RH readings for these three areas for a one-year period are shown in **Figures 2, 3,** and **4** on p. 12. Although these examples all neatly begin on January 1 and end on December 31, in practice it does not matter at what point in the year monitoring starts or stops; what is important is to have temperature and RH data for a long enough period to cover the major cyclical variations of the storage space.

The attic is cool and dry in the winter, warm and humid in the summer. The closet is a more moderate environment all year long, with some summer humidity. The basement is cool and humid all year round, with summer RH between 65% and 70%. All three environments show a seasonal trend toward worse conditions in the summer, but to varying degrees. In terms of chemical deterioration rate, which of these environments is best, and by how much? Do the attic's cold winters balance the too-hot summer? Are the

The Importance of Seasonal Changes

Preservation managers have lacked both the tools and the theory to evaluate the impact of storage conditions on the chemical decay rate of collections. They have had neither convenient devices for gathering the raw data, nor a method such as TWPI for interpreting such data. As the examples show, long-term temperature and RH monitoring is required. One may obtain a TWPI value for any length of time, but a two-week or one-month period does not tell much about a storage environment that undergoes seasonal changes. Because most changes are seasonal, at least one full "pass" through the seasonal cycle is necessary to adequately characterize TWPI. Data stretching over several years is even better, because it will reveal year-to-year differences. As in a mosaic, each individual piece of temperature and RH data forms only a small part of a larger picture, one whose meaning becomes apparent only when all the pieces are seen from a distance.

basement's cool temperatures offset by higher RHs? Would it be worth it to transfer collections from one of these spaces to another? No one can tell from looking only at the temperature and RH readings of **Figures 2, 3,** and **4,** but TWPI analysis easily can provide such answers.

Figure 5 is a plot of the PI and TWPI values for the attic. Consider first how PI values change through the year. (Remember, PI represents the "instantaneous" preservation quality for any given moment, based on the prevailing temperature and RH values at that time.) In January and February the attic is cold and dry, so the PI values run high, sometimes reaching 400 years on the coldest days. When summer comes the PI values plummet, reaching levels as low as seven years, only to increase again in the fall. The TWPI curve in **Figure 5** shows how PI values for the attic average out over time. When the TWPI calculation begins at "time zero" on January 1, PI and TWPI follow each other closely. After a while, the TWPI curve does not closely track fast dips and rises in PI values, because, as time passes, each interval of time forms a smaller and smaller portion of the cumulative average and so has less ability to pull the TWPI curve up or down. By late February, when the PI briefly shoots up to 400 years, the TWPI curve rises only slightly. The more time that goes by, the more "damped" the TWPI curve becomes, reflecting only long-term trends and not short-term changes.

During the attic's spring and hot summer, the TWPI curve declines steadily, reaching a low point in September. When the PI curve rises steeply during the cold temperatures of November, the TWPI curve hardly moves at all. At year's end the final TWPI value is only 29 years. Although the winter conditions were very good, the summer conditions were awful. The attic is a good example of the general principle in TWPI analysis that time spent at bad conditions "counts" for more than time spent at good conditions. It seems (with apologies to Shakespeare) that "the evil that bad conditions do lives after them."

Consider next the graph of temperature and RH for the closet (**Figure 3**). Temperatures are in the 60s for most of the winter, fall, and spring, while summertime temperatures are in the 70s and, occasionally, the 80s. RHs in the closet are moderate during winter and fall, but are higher during the summer, occasionally reaching 70%. In terms of human comfort, this environment would be considered a quite reasonable one, much better than the extremes of the attic. If there were a close correlation between human comfort and the rate of chemical decay, then the closet should be the best of the three environments for collection storage. The TWPI curve in **Figure 6** shows that the closet is better than the attic, but not by a great deal. Although the winter PIs are fairly good, the summer conditions help to lower the final TWPI in the closet to 36 years, only about 25% better than the attic.

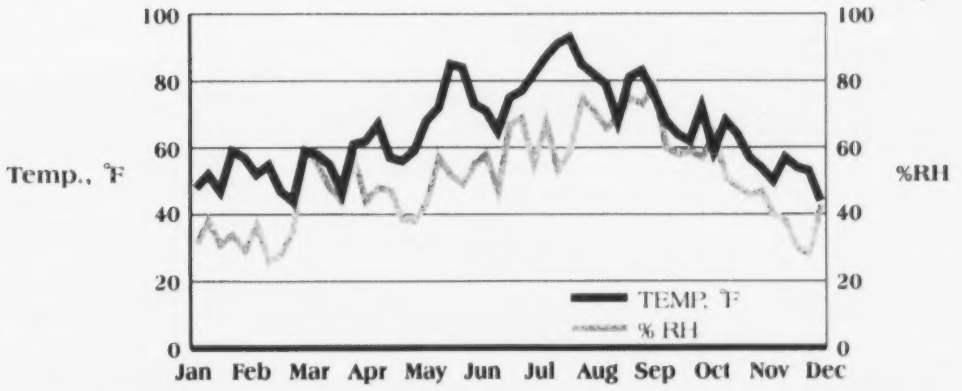


Figure 2. Attic temperature and RH.

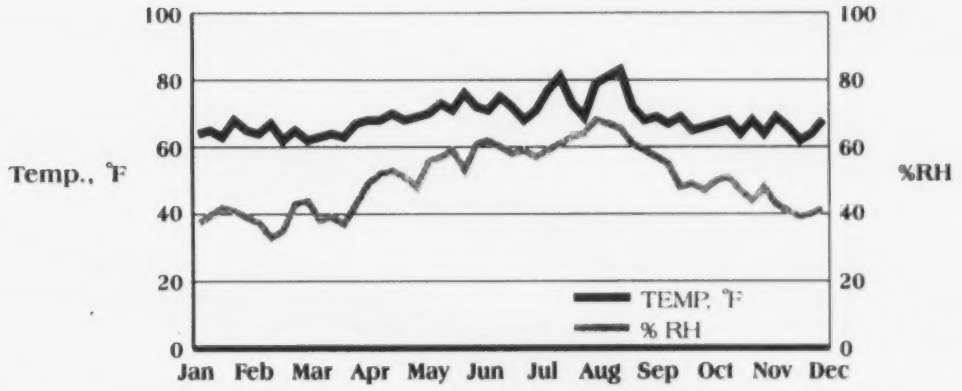


Figure 3. Closet temperature and RH.

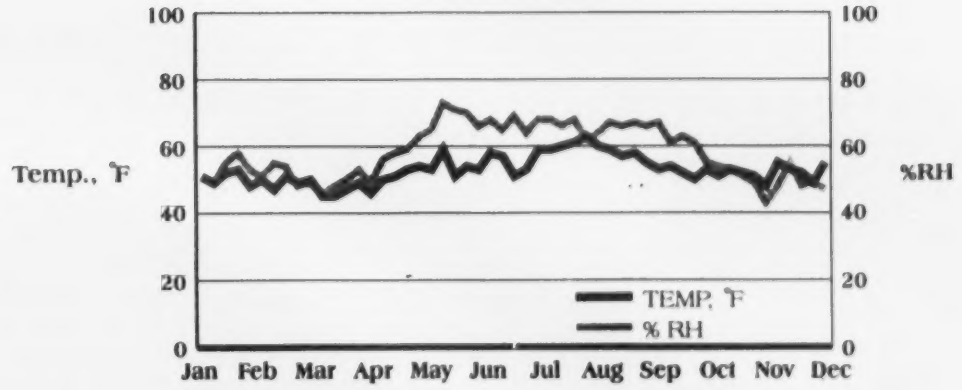


Figure 4. Basement temperature and RH.

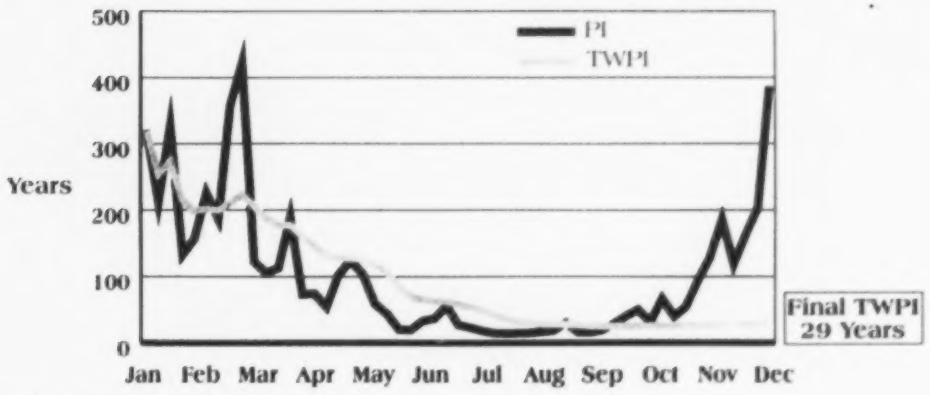


Figure 5. Attic PI and TWPI.

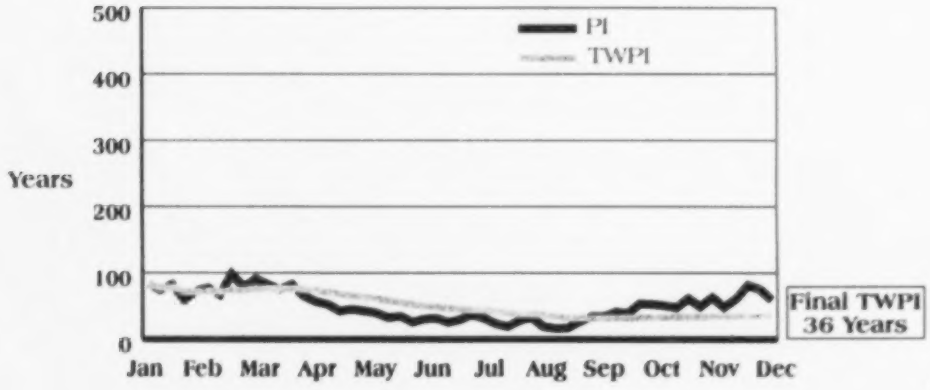


Figure 6. Closet PI and TWPI.

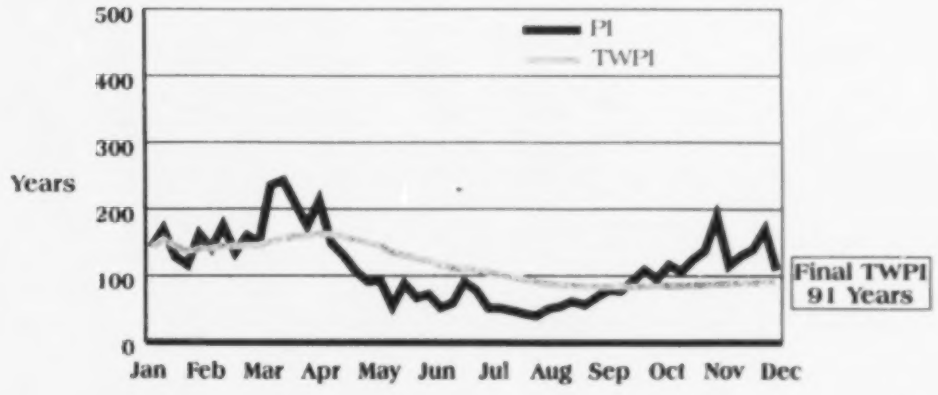


Figure 7. Basement PI and TWPI.

Temperatures in the basement (**Figure 4**) remain cooler than the closet throughout much of the year, rising slightly in the summertime. RHs in the basement are near 50% in the winter and fall and are between 60% and 70% during the summer. The plot of PI and TWPI for the basement (**Figure 7**) shows that winter and fall conditions in the basement are quite good, with PIs between 100 and 200 years. In the summer, the PI falls to around 50 years from May through September. Although this has the usual effect of lowering the TWPI, the fall brings a slight upturn in the TWPI curve, and the final TWPI for the year is 91 years.

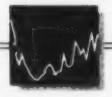
Thus, the final TWPIs of the three environments are:

Attic	**29 years**
Closet	**36 years**
Basement	**91 years**

Useful Insights from TWPI

In this example, the expected chemical lifetime of organic materials stored in the basement is about *three times longer than in the attic*, and *about two and one-half times longer than in the closet*. A factor of three is not a trivial difference in "preservation quality." It means that books would take three times longer to become brittle, that slides would take three times longer to fade, and that tapes would remain playable three times longer than if they were stored in the attic. Only TWPI analysis can make clear such differences among dynamically changing storage environments. TWPI is a fundamental property of storage environments that is critically important for preservation managers to know.

The main reason why the basement is three times better is its consistently cool temperatures. Note that by calling this hypothetical environment "basement" we do not mean to imply that basement storage in general is good for collections—often it is not, for a variety of other reasons which have nothing to do with chemical deterioration. The point of the example is to show that a cool but moderately humid space, as long as mold does not grow, can be better for slowing chemical decay than a warmer "human comfort" space. The basement environment in this example might well have been called "the castle," since it does help to show why northern European libraries in cool stone buildings—despite higher than ideal RHs—have much less of a brittle-book problem than overheated American libraries.



The Preservation Environment Monitor

We have seen that TWPI is a useful thing to know about the storage environment in a library or archive. In practice, how can the TWPI be measured? There are two main approaches. One is to load temperature and RH data into a computer and then calculate TWPI. Graphs of temperature, RH, PI, and TWPI like those in **Figures 2** through **7** can be obtained in this fashion. We used a spreadsheet program (Microsoft Excel®) to do the calculations, then made the graphs in CorelDraw®. The other approach is to build a device that combines both temperature and RH sensors with a microprocessor, so that TWPI values can be calculated and displayed in real time. In December 1994, IPI was awarded a grant from the Division of Preservation and Access of the National Endowment for the Humanities to develop both approaches and field-test them in up to 15 different institutions.

Over the course of two and one-half years, IPI will build and field-test a battery-powered device known as the Preservation Environment Monitor (PEM), which combines three functions in one: it measures and displays temperature and RH, it stores up to five years' worth of temperature and RH data for upload to a computer, and it displays PI and TWPI values in real time. Approximately 150 of the devices will be manufactured and given free to participating institutions during the project. IPI also will develop software for performing TWPI analysis on temperature and RH data gathered from conventional dataloggers. At the conclusion of the project a report will be produced which discusses the field-trial results and synthesizes what has been learned about environmental assessment using PI and TWPI. All of the technology developed in the project will be in the public domain. If the field trials are successful, IPI will continue to manufacture and support the PEM and software for TWPI analysis.

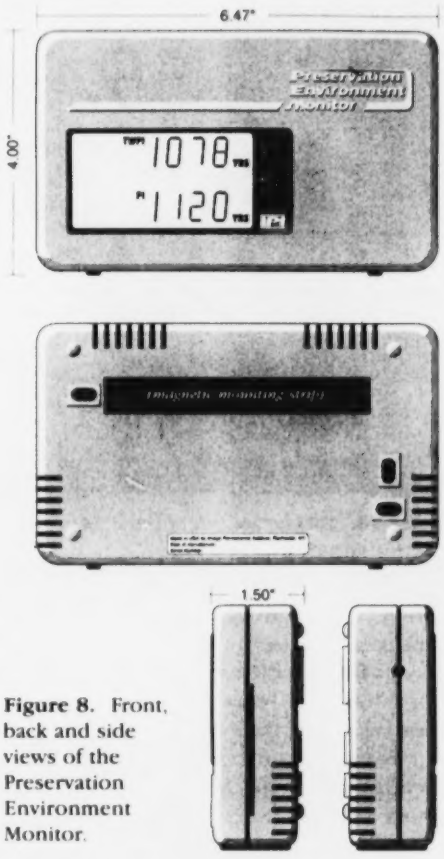


Figure 8. Front, back and side views of the Preservation Environment Monitor.

The PEM will be designed for use as an environmental monitor in libraries, archives, and museums. At the time of this writing, a detailed design specification for the device is nearly finished, and a solicitation for bids for design and manufacture soon will be released. A preliminary sketch of the device is shown in **Figure 8**. The design philosophy is one of lowest possible cost consistent with its function, simplicity of operation, ruggedness and reliability, and much better than customary accuracy in temperature and RH measurements. Whether or not all the desired features can actually be implemented at reasonable cost remains to be seen, but, in any case, the design process is interesting in and of itself because it is an opportunity to think about an ideal instrument for preservation monitoring.

The PEM design incorporates three levels of functionality. These are diagrammed schematically in **Figure 9**. On the first level, it is an accurate and precise temperature- and RH-measuring device. In recent years, the cost of electronic hygrometers has come down, even as their accuracy and reliability have increased. While accuracies of ± 2% RH over the range of 10% to 90% RH are now available in the best of the off-the-shelf instruments, reading the fine print of the specifications reveals that such accuracy applies only at room temperature, and the accuracy is considerably less at warmer or colder conditions. The PEM design will provide high accuracy over a much wider temperature range because it can use its microprocessor and data storage capabilities (which it needs for TWPI calculation) to correctly adjust the output of the RH sensor for changes in temperature. The PEM will be able to operate in cold vaults as well as near-sauna temperatures.

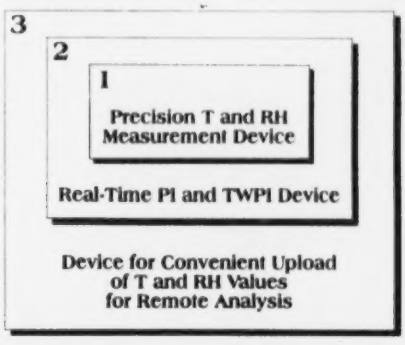

3
2
1
Precision T and RH Measurement Device
Real-Time PI and TWPI Device
Device for Convenient Upload of T and RH Values for Remote Analysis

Figure 9. Levels of functionality in the Preservation Environment Monitor.

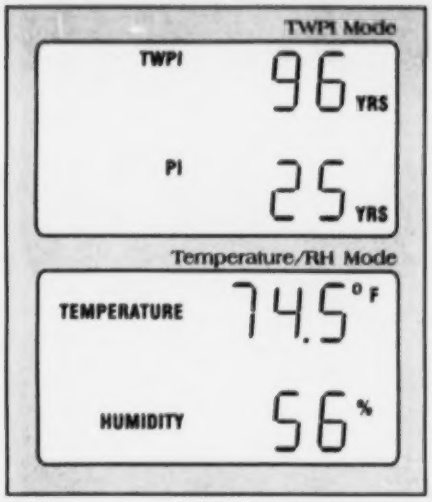


Figure 10. Display modes of the PEM. Modes alternate every 30 seconds.

The second level of functionality in the PEM includes the ability to calculate and display PI and TWPI in real time. The PEM has an LGD display that will show the temperature and RH for 30 seconds, then show the TWPI and PI for 30 seconds, alternating continuously. (See **Figure 10**.) In order to calculate PI and TWPI in real time, the PEM must have a microprocessor and have the PI definition table stored in nonvolatile memory. The PEM will update the temperature and RH frequently and will update the TWPI calculation every half hour. Users will be able to see the key facts about their storage environment at a glance.

The third level of functionality in the PEM includes the ability to act as a convenient means to collect temperature and RH data over long periods of time and to upload the data, at any point, to a computer for later analysis. In this respect, the PEM will function like many of the commercial dataloggers on the market, but with some important differences which make it more useful in the library and archives context. The PEM will store one full year's worth of temperature and RH readings taken every half hour. It will further store up to four additional years' worth of data taken at four-hour intervals. Thus it can hold five years' worth of data altogether—the last year's at half-hourly intervals, and the preceding four years' at four-hourly intervals. The half-hour data will be averages of more frequent readings, while the four-hour data will be the averages of eight previously stored half-hour readings.

A convenient aspect of the PEM is the method for retrieving the stored temperature and RH data for later analysis on a computer. Commercially available dataloggers use a cable which typically connects to the serial port of a computer; this means the datalogger must come to the computer, or the computer must be brought to the datalogger. The PEM will use a different approach. Each PEM has a small slot in the side of the case for the insertion of a PC Card (formerly PCMCIA). This is a credit-card-sized device that contains nonvolatile computer memory chips. Nonvolatile memory doesn't lose its data when the power is turned off. When the card is inserted, within seconds the PEM will upload all its stored data onto the PC Card. One card can hold the data from many monitors. The PC Card can be read by desktop PCs equipped with a PC Card reader. Most notebook and laptop computers already have the ability to use devices like PC Cards.

The PEM is designed to overcome the difficulties that hygrothermographs and dataloggers currently present to busy librarians and administrators. For those who only want "the answer," the PEM can be purchased and used as a real-time display device for temperature, RH, PI, and TWPI. Such users might never need or want the datalogger features and so would require nothing more than the PEM itself. Those who are interested and capable of doing their own data analysis can buy a PC Card and import the data into a spreadsheet such as Microsoft Excel®. The convenience of uploading the data into the PC Card, however, will make it possible for users to send off the cards to a service provider, who would return an expert analysis complete with graphs of temperature, RH, PI, and TWPI. Analysis of the potential for mechanical damage or biological attack might also be included. Much of this task could be automated, requiring only a brief check by a specialist to look for unusual or dangerous conditions. In this way, long-term environmental data together with expert analysis could be delivered cheaply and conveniently to collection managers. IPI may be interested in providing such a service.

Guidelines for Application of PEM

Practical applications for the PEM are obviously of critical importance in the field trials. The following are general application suggestions that IPI will make to participating institutions. The purpose of the field trials is to develop these ideas in detail.

A key practical use is the ranking of alternative storage areas. Sites will receive several monitors so they can monitor a number of different rooms at once over a six-month or (preferably) one-year period. By analyzing PIs and TWPIs during the trial, they can have an ongoing seasonal profile, seeing which areas are best during summer and winter and over the whole year. A simple table of annual TWPIs will show which are the best storage environments, which need improvement, and how much variation there is among existing spaces. Because both temperature and RH influence deterioration, it is not always clear which storage spaces are best—especially because temperature and RH vary in most real-life storage circumstances—and this makes comparison difficult. The PEM should greatly simplify the difficulties of deciding which areas are better than others, and by how much.

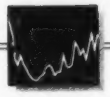
A second application is exploring differences *within* a room. Users can employ one monitor or several to determine floor-to-ceiling temperature stratification or to compare parts of a room. Such differences can become clear within a relatively short time. IPI will explain how to use the PEM's reset function when starting to evaluate a new location.

A third application is exploring the microclimate inside closets, cabinets, shelves, or even boxes. Certain important items or particular storage systems such as compact shelving exist in their own semi-sealed microclimate, which may be significantly different in character from the room environment. Two PEMs can give an idea of the differences between the isolated microclimate and the room conditions.

A fourth application is to use the PEM to obtain instant feedback on small or large attempts to improve the collection storage environment. Perhaps the most useful thing about the PI/TWPI approach is that it encourages incremental changes in environment by showing that even small improvements can have a powerful effect on collection preservation. Using the PEM, the results of an effort to improve conditions can be seen immediately as a change in PI. This type of incremental action is especially important for smaller institutions, though it applies to larger ones as well. We are especially interested in this aspect of the field trials of the PEM and will encourage all participating institutions to dedicate one or two PEMs as "barometers" for small incremental changes.

The PEM as a Survey Tool

One of the more interesting applications of the PEM is its use in environmental assessment surveys. Often the first step toward organized preservation and conservation in a small library or museum is a survey, performed by a private consultant, a regional center, or large nearby museum or archives. One of the first items of business is to evaluate storage conditions and to help the institution become more conscious of the importance of the storage environment. The PEM will help make the connection between temperature, RH, and collection life expectancy more real to staff in the institution because they can see for themselves that PI decreases when temperature and RH increase, and vice versa. Those performing the survey can use the measured PI and TWPI values as a basis for discussions with the staff and help them compare their environment with what is achieved in similar institutions elsewhere.



Appendices

Appendix I

Forms of Deterioration in Organic Collection Materials

Appendix II

Technical Basis for the PI Concept: Background on Deterioration Mechanisms and Test Methods

Appendix III

Technical Basis for the PI Concept: Specific Origins of the Preservation Index Model

Appendix IV

Temperature and RH Equilibration in TWPI Analysis

Appendix 1

Forms of Deterioration in Organic Collection Materials

Preservation managers must be concerned with many possible threats to their collections. Leaving aside natural disasters, theft, and mishandling, there remain the slower and more subtle forms of deterioration,[8,19,22] which may be divided into five general types: chemical, pollutant-induced, light-induced, biological, and physical.[7,19,20] Chemical deterioration is described on p. 2.

Pollutant-Induced Deterioration

Pollutant-induced forms of deterioration such as tarnishing of silver have a strong RH dependency and involve chemical reactions, but they are considered a separate category from inherent chemical deterioration in that pollutants are external to objects and, hence, are not always present. Pollutants can affect both organic and inorganic materials in storage. In practice, pollutant-induced deterioration is dealt with by air purification systems and the use of protective enclosures.[23] The technology to detect and control pollutants is an important part of preservation, but pollutant attack is material-specific and quite different from heat- and RH-induced chemical deterioration.

Light-Induced Deterioration

Light-induced deterioration primarily affects organic materials. Light is a form of energy that breaks chemical bonds, thus causing decay. The damage caused by light depends mainly on the nature of the object, the RH, the kind of light or other radiant energy present (e.g., UV, IR), the intensity, and the duration of exposure.[22] Light-induced deterioration is controlled in various ways, but principally by keeping illumination intensities down and storing objects in dark places.

Biological Deterioration

Biological forms of deterioration primarily affect organic materials and can be divided into three main categories: bacterial, fungal, and insect-related. Temperature and RH are important factors for all three forms of attack, but the ways in which environmental conditions facilitate or inhibit such forms of deterioration are complex.[19] Fungal growth requires high RH, but it depends on temperature, too. Bacterial growth is strongly temperature-dependent, but it is also affected by RH. Insect damage depends in part on both temperature and RH. In general, biological forms of deterioration depend on a complex interplay of the specific organisms involved, the nature of the objects in the collection, temperature and RH conditions, and other factors, such as light, ventilation, and housekeeping practices. Predicting the occurrence and severity of such deterioration is often difficult, and control measures must be tailored to the particular circumstances of each collection.

Physical Deterioration

Problems such as warping of parchment sheets and wooden panels, splitting of wood veneers, gelatin delamination of glass plate negatives, and shrinkage of fabrics are primarily *physical* or mechanical forms of deterioration.[8,9,20] Collections of exposed objects of wood, parchment, and so forth, are most at risk from physical deterioration. Changes in

moisture content of these materials cause them to swell or shrink. When such reversible dimensional changes are uniform and unrestrained they usually do no harm. Sometimes, however, if layers that swell are bonded to layers that do not, or if one part of an object has more moisture than another, deformations, delaminations, or cracks will result. Both swelling and shrinking can be destructive, and such problems can occur at any time in the life of a susceptible object. RH is the principal environmental factor concerned here; as long as the moisture content of the objects remains fairly constant, temperature changes or the absolute level of temperature have relatively little bearing on these problems. (Temperature changes, however, have a big effect on chemical deterioration.)

Fast RH changes and extremes of RH are the primary environmental causes of physical deterioration. Some materials are notoriously sensitive to them, while others are not. With a very few exceptions, RH changes within a range of about 10% are not a concern, even for susceptible materials. For laminated materials, what is typically most dangerous is a fast drop in RH of 40% or more.[24] For information collections (books, paper, film, photographs, video, and sound) chemical deterioration is a far bigger threat than physical deterioration. These materials are not among the most sensitive to RH fluctuations, and they very rarely experience them in any case, because fast RH change is buffered by the packaging and enclosures in which they are customarily stored.[25]

Appendix II

Technical Basis for the PI Concept: Background on Deterioration Mechanisms and Test Methods

The PI concept is a general model of how environment affects the rate of decay in organic materials. The place to begin the discussion of the technical basis for the PI concept is with the processes of decay themselves. Virtually all organic materials in archives undergo the same basic chemical reactions of deterioration. The most common reaction, assuming that the air in the storage area is reasonably free of pollutants, is one in which moisture degrades the organic material. The speed of this reaction, in the presence of constant moisture, is governed by temperature in a predictable way in accordance with well-established chemical kinetics rules. However, this reaction, called *hydrolysis* (from the Greek, *hydro* = water and *lysis* = to break or separate), is also, as the name implies, rate-dependent on the amount of moisture available. In general, the moisture content of an organic material is dependent on the RH of the storage area, and therefore the rate of degradation by hydrolysis is also dependent upon the RH.

In the absence of moisture, the second fastest reaction, *oxidation*, will predominate. In clean air, this reaction involves the combination of the organic material with oxygen from the air. This is effectively what fire does, but slow oxidation occurs at a greatly reduced rate and much less completely. Oxidation is generally a very much slower reaction than hydrolysis. In the absence of both air and moisture, *thermal degradation* (the spontaneous breaking of chemical bonds because atoms and molecules are in motion) is the predominant reaction. This reaction is much, much slower than either oxidation or hydrolysis. All of these reactions occur together and compete in real life. Because of the great differences among the relative reaction rates, usually only the predominant reaction is considered. For all three types of reactions, however, the rate of deterioration under fixed moisture conditions often follows well-established laws with respect to the dependence of reaction rate on temperature. It is because of this orderly behavior that it is possible to use results from accelerated, high-temperature experiments to predict the rate of reaction at more normal, cooler conditions. This kind of accelerated-aging test is known as "Arrhenius testing." However, because the effects of RH on deterioration rate do not follow any well-established laws, it is necessary to determine the RH effects empirically.

Arrhenius Testing: Reaction Rate Determinations from Accelerated-Aging Studies

All the published data that relate environment to the rate of chemical deterioration come from what is called "Arrhenius" testing. Named in honor of a nineteenth-century Swedish chemist, this approach uses accelerated aging to determine how temperature affects reaction rate.[26,27] In such tests, RH is held constant, and temperature is varied. By measuring how many days it takes for a predetermined amount of deterioration to occur at various temperatures, it is possible to make a graph of "time to deteriorate" vs. temperature. **Figure 11** shows a sample Arrhenius graph without data points. Note that there are some "tricks" in the way in which time and temperature are plotted. Time is plotted on a logarithmic scale; each unit on the time axis goes up by a factor of 10 times: 1 day, 10 days, 100 days, etc. Temperature is plotted on a reciprocal scale as 1/T, so that the highest temperatures are near the origin of the graph, and the lower ones are further

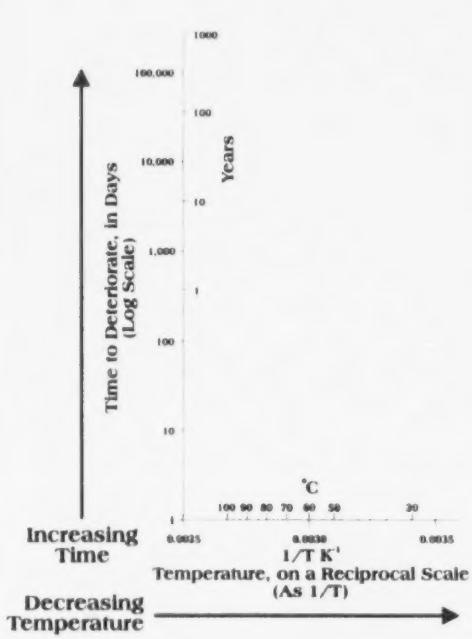


Figure 11. Sample Arrhenius plot, axes only.

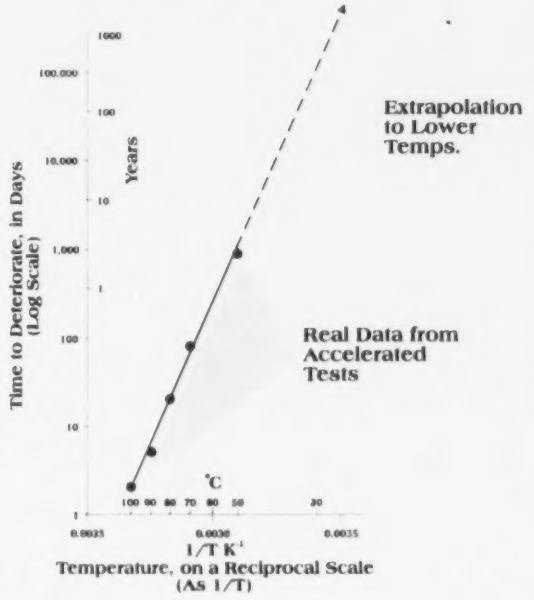


Figure 12. Sample Arrhenius plot with data.

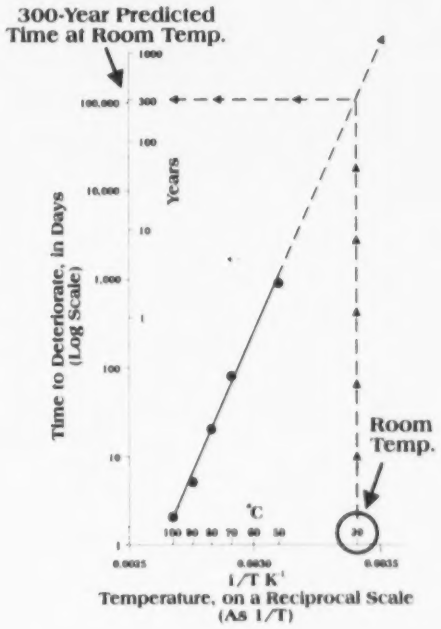


Figure 13. Sample Arrhenius plot showing predicted time to deteriorate at room temperature.

away. Chemical kinetics theory says that if data from accelerated tests fall on a straight line when the axes are set up in this fashion, then the data show an orderly behavior that agrees with the theory.

Only one point can be placed on the graph for each different temperature used in the accelerated-aging experiments. Ideally, all points fall on a straight line. The payoff to all this is that simply by extending the line to lower temperatures (i.e., below those actually used in the accelerated aging), it is possible to predict how long it would take for the same amount of deterioration to occur at any temperature, from room temperature down to cold storage conditions. **Figure 12** shows a sample Arrhenius plot with five data points on it. The solid line connecting the points covers the range of temperatures actually used in the experiments. The dotted extension of the line represents *extrapolated* (predicted) behavior at lower temperatures than those used in the testing.

From an Arrhenius plot, it is possible to determine a predicted time for deterioration to occur at any temperature. **Figure 13** shows a sample Arrhenius plot illustrating how a predicted life at room temperature (20°C) is obtained. Starting from the temperature axis, locate the 20°C point. Follow that straight up until it intersects with the Arrhenius line. Then go straight across to the time axis and that is the predicted deterioration time at 20°C. In this example it is 300 years.

Arrhenius plots have two significant features: the slope of the straight line and the point where the line crosses room temperature (customarily 20°C). This point is called the "room temperature intercept." The *slope* is the steepness of the line; it expresses how much of an influence temperature has in determining deterioration rate. A shallow, low slope on the Arrhenius line means the reactions of decay are not much affected by storage temperature. They will proceed at almost the same rate regardless of temperature. On the other hand, a high, steep slope means that small changes in storage temperature will mean a large change in deterioration rate.

Activation Energy: Temperature's Influence on Reaction Rate

To a physical chemist, the slope of the line on an Arrhenius plot represents the "activation energy" of the reactions of deterioration. In a way, activation energy (usually expressed in units of kilocalories) is a kind of "energy payment" that must be made if two otherwise stable molecules are going to react with each other. In a physical sense, it is the energy needed to loosen chemical bonds and put them in a state where they can be broken and re-formed by reacting with something else. Heat energy from the surrounding environment often provides the requisite energy payment, so nearly all reactions go faster at higher temperature, although substances do differ in terms of how much energy it takes to "activate" molecules and cause the reactions of decay.

Activation energy is therefore a direct measure of the temperature dependence of the deterioration rate. Materials that degrade with a *high* activation energy will have a much greater life expectancy with small *reductions* in temperature. However, by the same token, deterioration also will be much faster with small *increases* in temperature. For these high-activation-energy materials, bad conditions are very bad, and good conditions are very good. Similarly, materials with a very *low* activation energy of deterioration will require large improvements in storage conditions in order to produce a significant increase in life expectancy. However, they also deteriorate less rapidly when the temperature goes up. This "double-edged sword" behavior of activation energies might be compared to interest rates. High interest rates are very nice for a savings account, but they make repaying a loan much more costly. Low interest rates are the opposite—nice for borrowing, but it also takes much longer to build up capital in a savings account.

Table of Published Activation Energies

Since the PI concept includes a general model of temperature effects on deterioration and incorporates an activation energy of approximately 22 kilocalories, the PI model ought to be consistent with published activation energy data, and it is. **Table III** shows a list of published activation energies for some culturally important organic materials. This is a partial but representative list. The type of material, form of deterioration, and test RH are also shown. Of the 52 experimentally determined activation energies, the mean value is 24 kcal. The highest value is 35 kcal, and the lowest 14 kcal. **Table III** shows that materials have varying activation energies for deterioration, but a value in the low to mid-20s is a reasonable "middle-of-the-road" representation of the temperature dependency behavior of organic materials in general.

Arrhenius testing can determine the influence of temperature on deterioration, but, in order to include the effects of RH, several series of Arrhenius tests must be done at differing humidities. A successful technique is to do Arrhenius tests at 20%, 50%, 60%, and 80% RH, then interpolate between them. With a little extrapolation to slightly higher and lower RH values (5% to 95%), this technique can give an estimate of the deterioration rate at nearly any storage condition.

"Intercept": Predicted Life at Room Temperature

The other significant feature of the Arrhenius line is its *room-temperature intercept*. As stated above, this refers to the point on the graph where the extrapolated straight line crosses room temperature. Since each point on the line has both a temperature coordinate and a corresponding "time for a predetermined amount of deterioration" coordinate, the room-temperature intercept is important because it tells how much time will pass at room temperature before the predetermined level of deterioration occurs. In practice, this is one thing preservation managers need to know, and the room temperature intercept is also a handy benchmark with which to compare materials. Rag paper and groundwood paper may have the same slope on an Arrhenius plot, but the expected lifetime at room temperature is likely to be much shorter for groundwood than for rag paper.

Can We Trust Accelerated Aging?

Many materials of cultural importance have been characterized by means of Arrhenius testing, with the goal of understanding their future behavior at moderate or cool temperatures. In fact, the Arrhenius approach is the only *predictive* type of accelerated aging; it is the only way to estimate future behavior.[26,28] People are understandably skeptical about the predictions that are derived from accelerated-aging tests. Such tests are very complex to do and the interpretation of them often involves a daunting array of caveats and qualifiers.[29] Can they be trusted? On what basis do they rest?

The best way to answer these questions is to consider that Arrhenius testing rests on a very solid foundation of classical chemical kinetics, the study of reaction rates. If the principles of kinetics (including all that was discussed above about activation energy and temperature) are wrong, then many of the chemical products of the modern world could not have been produced. Chemical engineers use these principles every day to design plants and processes, confident that kinetics will help them understand what temperatures, pressures, and times they need to make reactions occur on schedule. To categorically distrust all accelerated aging is to ignore the reality that chemical kinetics is a functioning branch of science that is not just theory but proven in practice. No one suggests that accelerated-aging tests are flawless, but they do give the best available indication of what will happen to materials over time.

Table III. Published activation energies for deterioration of culturally important organic materials.

Material Type	Form of Deterioration	Test RH	Activation Energy, kcal	Source of Data (Ref. #)
Color Photographic Print	30% Dye Fade, Cyan Dye	50%	24	IPI Fuji (30)
Color Photographic Print	30% Dye Fade, Cyan Dye	50%	19	IPI Fuji (30)
Color Photographic Print	30% Dye Fade, Cyan Dye	50%	26	IPI Fuji (30)
Color Photographic Print	30% Dye Fade, Cyan Dye	50%	23	IPI Fuji (30)
Color Photographic Print	30% Dye Fade, Cyan Dye	50%	21	IPI Fuji (30)
Color Photographic Print	30% Dye Fade, Cyan Dye	50%	23	IPI Fuji (30)
Color Photographic Print	30% Dye Fade, Cyan Dye	50%	22	IPI Fuji (30)
Color Photographic Print	30% Dye Fade, Cyan Dye	50%	23	IPI Fuji (30)
Color Photographic Film	30% Dye Fade, Cyan Dye	50%	28	IPI Color Microfilm (31)
Color Photographic Film	30% Dye Fade, Cyan Dye	50%	26	IPI Color Microfilm (31)
Color Photographic Film	30% Dye Fade, Cyan Dye	50%	26	IPI Color Microfilm (31)
Cellulose Acetate Plastic	"Vinegar Syndrome," 0.5 Free Acidity	20%	22	IPI SMPTE (5,6,32)
Cellulose Acetate Plastic	"Vinegar Syndrome," 0.5 Free Acidity	50%	21	IPI SMPTE (5,6,32)
Cellulose Acetate Plastic	"Vinegar Syndrome," 0.5 Free Acidity	60%	21	IPI SMPTE (5,6,32)
Cellulose Acetate Plastic	"Vinegar Syndrome," 0.5 Free Acidity	80%	20	IPI SMPTE (5,6,32)
Cellulose Nitrate Plastic	0.5 Free Acidity	50%	28	IPI Acetate 2 (33)
Cellulose Nitrate Plastic	0.5 Free Acidity	50%	31	IPI Acetate 2 (33)
Photographic Gelatin	Wet Strength, 50 g	20%	26	IPI SMPTE (5,6,32)
Photographic Gelatin	Wet Strength, 50 g	50%	27	IPI SMPTE (5,6,32)
Photographic Gelatin	Wet Strength, 50 g	60%	30	IPI SMPTE (5,6,32)
Photographic Gelatin	Wet Strength, 50 g	80%	27	IPI SMPTE (5,6,32)
Magnetic Recording Tape	Binder Hydrolysis, Extractable Products	100%	14	Cuddihy (13)
100% Cotton Paper, Rosin Size	Fold Endurance, 50% Decrease	50%	33	Browning & Wink (12)
100% Cotton Paper, Aquapel Size	Fold Endurance, 50% Decrease	50%	35	Browning & Wink (12)
Bleached Chemical Wood Pulp Paper	Fold Endurance, 50% Decrease	50%	31	Browning & Wink (12)

(Continued on page 26)

Table III. Published activation energies for deterioration of culturally important organic materials. *(Continued from page 25)*

Material Type	Form of Deterioration	Test RH	Activation Energy, kcal	Source of Dat (Ref. #)
Bleached Chemical Wood Pulp Paper	Fold Endurance, 50% Decrease	50%	30	Browning & Wink (12)
Printing Paper	Fold Endurance	50%	27	Gray (10,11)
Printing Paper	Fold Endurance	50%	26	Gray (10,11)
Printing Paper	Fold Endurance	50%	23	Gray (10,11)
Printing Paper	Fold Endurance	50%	22	Gray (10,11)
Printing Paper	Fold Endurance	50%	20	Gray (10,11)
Copy Paper	Fold Endurance	50%	31	Gray (10,11)
Copy Paper	Fold Endurance	50%	25	Gray (10,11)
Copy Paper	Fold Endurance	50%	27	Gray (10,11)
Copy Paper	Fold Endurance	50%	21	Gray (10,11)
Copy Paper	Fold Endurance	50%	21	Gray (10,11)
Copy Paper	Fold Endurance	50%	27	Gray (10,11)
Copy Paper	Fold Endurance	50%	33	Gray (10,11)
Copy Paper	Fold Endurance	50%	29	Gray (10,11)
Copy Paper	Fold Endurance	50%	25	Gray (10,11)
"New Fibers" Paper	Fold Endurance	50%	21	Gray (10,11)
"New Fibers" Paper	Fold Endurance	50%	22	Gray (10,11)
"New Fibers" Paper	Fold Endurance	50%	21	Gray (10,11)
"New Fibers" Paper	Fold Endurance	50%	24	Gray (10,11)
"New Fibers" Paper	Fold Endurance	50%	24	Gray (10,11)
"New Fibers" Paper	Fold Endurance	50%	26	Gray (10,11)
"New Fibers" Paper	Fold Endurance	50%	25	Gray (10,11)
"New Fibers" Paper	Fold Endurance	50%	26	Gray (10,11)
"New Fibers" Paper	Fold Endurance	50%	19	Gray (10,11)
"New Fibers" Paper	Fold Endurance	50%	23	Gray (10,11)

Appendix III

Technical Basis for the PI Concept: Specific Origins of the Preservation Index Model

The PI general model of chemical deterioration in organic materials relates storage temperature and storage RH to the rate of deterioration. Thus, there were three key choices to be made in the creation of the PI model: activation energy (temperature dependence), time values, and RH dependence.

Activation Energy/Temperature Dependence

In order for PI to be a good *general* model of temperature effects on deterioration rate, it should be based on an activation energy that is in the "lower-middle" range of those found in **Table III**. This would ensure that the temperature dependence of deterioration would be accurately and conservatively characterized. Such an "average" choice would represent many materials' behavior and minimize the error that the choice of a high or low extreme would introduce. It would limit false hopes based on inadequate environmental improvements, and it would also tend to reduce overreaction to small negative changes in the environment. Too low an activation energy for the general model would cause the user to expect very limited changes in life expectancies from alterations in the storage environment. Too high an activation energy would make small improvements look very potent, but it would also tend to exaggerate the dangers of poor conditions, making preservation seem hopeless.

Thus, choosing a lower-middle activation energy value means that, for most materials, any positive improvements in storage conditions would have *at least* the payoff in improved life expectancy that the PI value says it will. Conversely, negative environmental changes to warmer and moister conditions would be *at least* as bad as the PI says, though they might be even worse. In order to have a general model at all, only one activation energy value can be selected, and there will necessarily be trade-offs between overstating and understating the relative impact of bad and good conditions, because not all materials have the same activation energy. The choice of activation energy value is in part a judgment call about the pattern of use of the PI measurement in preservation practice.

Preservation managers who take any action on the basis of PI and TWPI values will likely be making improvements to the storage environment. A slightly lower than average activation energy can be relied upon not to overstate the payoff from making small or large improvements in storage conditions. **Table III** shows activation energies that range from 14 to 35 kcal. A value in the low 20s would fit this requirement. Some materials (for example, nitrate film) may deteriorate even faster under poor conditions than the PI indicates, but on balance it is more important to be sure of the benefits of a good environment than the dangers of a bad one.

Time Values Chosen for the PI Model

The time values of the PI model were chosen deliberately to reflect the life expectancy of short-lived materials such as acetate film or poor-quality paper, i.e., about 50 years at room conditions. The PI can then be taken at face value as an approximate life expectancy in years for inherently unstable materials in that environment. Unstable

materials are the ones with which environmental preservation strategies are most often concerned. For ***inherently longer-lived materials*** (those whose activation energy is similar but whose intercept point at room temperature is much longer), the PI values could not be taken as an indication of approximate lifetime, but they would still be correct in a ***relative sense***. For example, groundwood paper is an inherently unstable material, and the PI expresses an approximate life for such a material. Rag paper will last much longer at any storage condition than groundwood paper. But if improvements are made that double the PI of the storage area, then the rag paper would also last twice as long.

RH Effects in the PI Model

The RH dependence of the PI data set ideally should be based on experimentally derived data, not just an estimate. Though Arrhenius tests need not be done at every RH value, the more empirical RH data, the better. In the few comprehensive studies that have been done, activation energies do not vary much with RH, but the room temperature intercept (the absolute life expectancy) varies by a factor of about ten times over the range of humidities from low to very high.[5,6,32,33,34] The ideal data set to use in formulating the PI model would be data from empirical studies in which a range of humidities was used. Intermediate RH levels not included in the test program could be obtained from interpolation between the humidities actually tested.

IPI Acetate Film Data Used To Define PI Data Set

The data obtained by IPI in its 1988–1990 study of deterioration rates in cellulose acetate plastic film supports[35] make an excellent and convenient choice for use as the PI general model. The precise form of deterioration measured in the study was "vinegar syndrome": the buildup of acetic acid in the cellulose acetate support, primarily as a result of hydrolysis. Cellulose acetate has the appropriate activation energy (approximately 22 kcal at all RH levels), the appropriate intercept (44 years at 68°F, 50% RH), and its RH dependence has been characterized from actual experimental work. Acetate film is a material of considerable significance in archival and library collections and one that is closely related in chemical structure to paper and cotton. IPI's research on cellulose acetate film base deterioration is one of the few large-scale Arrhenius studies to cover a wide range of humidities (four were included: 20%, 50%, 60%, and 80% RH). IPI's acetate data actually are derived from *two* complete Arrhenius test programs;[32,35] IPI undertook a second large Arrhenius research project in 1991–1994 that examined a number of acetate films for a second time, with essentially similar results. Since the data set for PI will be the exact data published in the "wheel" of the *IPI Storage Guide for Acetate Film*, it is already available in a convenient form for rough-and-ready estimation of environmental effects when computerized analysis of temperature and RH records is not possible.

How the PI Model Compares with Other Published Models

In the library and archives preservation field, three models relating storage conditions to collection life expectancy of specific materials have recently been published. The first, Donald Sebera's *Isoperms, an Environmental Management Tool*[1] deals with paper deterioration. The second, the *IPI Storage Guide for Acetate Film*,[36] deals with decomposition of cellulose acetate film base. The third was the National Media Lab's *Magnetic Tape Storage and Handling*,[7] which includes a model of environmental effects on the life expectancy of Hi Grade VHS tape. There is a fourth such model which is about to be published, dealing with the fading rate of dyes in contemporary color photographs. This model was prepared by IPI during a grant from the New York State Library Preservation Discretionary Grant Program, and will be issued as a publication of the New York State Library in early 1996.[36] Like the acetate and VHS tape models, the color dye fading model was based on extensive accelerated-aging tests.

How well do these models agree with each other? Can there be one general model which represents the behavior of many materials and thus becomes a broadly useful tool for assessing storage environments? In **Table IV** the four models are compared. The predicted life expectancy, in years, of the various materials are shown for five different storage conditions. Also shown are the average predictions of the four models for each storage condition. (The relative factors used in the *Isoperm* model were converted into life expectancies by assuming that an isoperm value of 1 was equal to 44 years, which is the LE of the PI model at 68°F, 50% RH.)

Table IV. Comparison of five models of chemical decay.

	Life Expectancy Value, Years				
Model/Material	**70°F 80% RH**	**70°F 50% RH**	**70°F 20% RH**	**50°F 50% RH**	**30°F 50% RH**
IPI/Acetate Film[45]	17	38	87	158	731
Isoperm*/Paper[1]	26	41	92	220	1540
NML/VHS Tape[7]	6	32	>64	>>64	>>64
NYS-IPI/Color Dyes[36]	18	38	182	169	843
Average	**17**	**37**	**106**	**182**	**1038**

*Using 25 kcal/mole, normalized to 44 years at 68°F, 50% RH.

If the models agreed perfectly, all the numbers in the columns of **Table IV** should be the same. In fact, they are remarkably close, especially at near-room temperature where most things are actually stored. At low RH and at extreme low temperature there are some larger differences, but at 50°F the models are still quite close. At 30°F the largest difference is between a 700-year predicted life and a 1500-year predicted life—only a factor of two. In any case, seven centuries or fifteen centuries are rather abstract quantities in practical terms, and the error inherent in all predictive models begins to be significant when such long lifetimes are involved. To us, and to those who work regularly with accelerated-aging data, this agreement among predictive models was significant and somewhat unexpected.

The point of showing the similarities among these published models for different materials is to suggest that choosing one of them and calling it the "general" model is a reasonable thing to do. IPI chose its acetate film data for the Preservation Index model, but any of the models would convey the same basic trends, and lead to the same kinds of quantitative judgments about the effect of temperature and RH on the "chemical lifetime" of collections. Differences among materials do exist; color dyes last relatively longer at low RH than other materials, for example. Materials still should be investigated and characterized individually in order to understand their behavior. But such differences are not enough to obviate the practical value of an overview of how environments affect deterioration rate.

Appendix IV

Temperature and RH Equilibration in TWPI Analysis

TWPI analysis can deal with dynamically changing environmental conditions. However, some compensation must be made for the fact that temperature and RH changes are not immediately "felt" by objects in collections. When the temperature of the air in a room changes, the objects in that room do not instantly attain the same temperature.[19,22] There is a delay, or lag, in coming to equilibrium that depends on the nature of the object, its mass, its shape, its surface area, and the velocity of air circulation around it. The fact that a frozen turkey takes longer to thaw than a frozen chicken demonstrates how differences in mass affect the time required to achieve complete temperature equilibration. Any packaging that may surround objects usually does not significantly slow down the process of temperature equilibration, because heat flows readily through most materials.

A similar "equalization" process occurs with RH changes, except that RH equilibration is usually much slower than temperature equilibration. Most organic materials absorb water from the atmosphere to an extent that is governed by the prevailing RH and by the nature of the material itself. Objects absorb moisture when the RH goes higher and, conversely, desorb it when the RH goes down. RH equilibration is not only a slower process than temperature equilibration, it is also more complex; in addition to the above-mentioned factors that govern heat transfer, there is also the strong influence of packaging and enclosures. The plastic wrapping of the frozen turkey does not impede its thawing, but it keeps it from drying out. Cabinets, boxes, folders, and sleeves all contribute to differences in the rate of RH equilibration for objects in collections.

Compensating for Differences in Temperature and RH Equilibration Rates

Returning to the larger issue of the rate of chemical deterioration of collection materials, what really matters is the actual temperature and moisture content of the *objects*, not of the room air. TWPI analysis must, therefore, accommodate for the time it takes for temperature and RH equilibration to occur. For the reasons just listed, this will not be exactly the same for all types of objects, or even for similar objects in varying storage circumstances. Ideally, one should use temperature/RH values in the calculation of PI that correspond to the actual temperature and moisture content of the objects in the collection. In practice, however, sensors can only measure the air around objects, and so it is necessary to estimate the length of time between a change in room conditions and the point at which the objects in the room actually "feel" the change.

A simple experiment performed at IPI demonstrates the realities of temperature and RH lagging for a book on a shelf. Two dataloggers were employed, one placed in open air near the book, and the other placed inside a form-fitting, hollowed-out space inside a moderately thick book (24 cm high, 17 cm wide, 8 cm thick) placed on a filled shelf among other books. The bookshelf was of open design, typical of those found in libraries. The IPI Library is an air-conditioned room, controlled (but not very well) to an RH set point of 50%.

In **Figure 1**, the RH conditions outside the book are compared with those recorded by the datalogger inside the hollowed-out book for the five-month period from October 1994 to March 1995. Two facts are readily apparent. First, the RH inside the book does

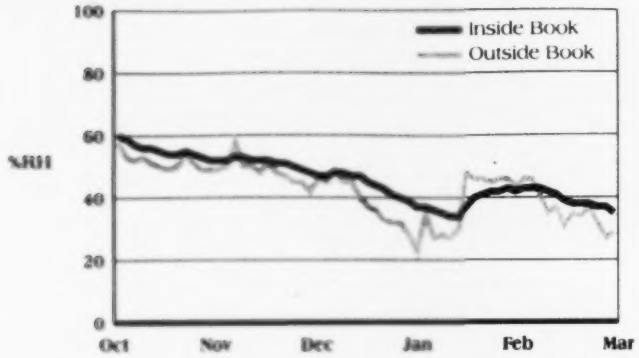


Figure 14. RH inside and outside a book in the IPI Library for a five-month period.

indeed follow the long-term trends in room RH, but is very slow to respond. Second, fast changes in room RH are "damped" by the slow response, causing the plot of the inside-the-book RH to be much flatter than that of the room air. Short-term changes in room RH simply were not "felt" deep inside the book. For example, in mid-January, repairs to the humidifiers caused a rapid increase in room RH, from about 25% to 50%. It took about one month for the RH inside the book to catch up with the room RH. In early February, the room RH declined once again, and the RH inside the book remained higher than the RH outside for the rest of the month. This latter point also illustrates one of the complexities of RH equilibration: the fact that desorption of moisture, particularly at low RHs, is often slower than absorption of moisture.

Temperature data inside and outside the book for the same period are not shown because, on a five-month time scale, the two curves would appear superimposed on each other. The two curves have essentially the same shape because temperature equilibration occurs much more rapidly than humidity equilibration. Examination of the two curves would show that inside-the-book temperatures almost always reached outside room air levels, unless the room air temperature was changing very fast. The two curves are shifted slightly in time, with the inside catching up with the outside in about six to 12 hours. Of course, this simple experiment does not represent all objects' behavior, but it does confirm that temperature equilibration is much more rapid than RH equilibration for a book on a shelf, and it gives some idea of the actual lag times involved.

Temperature Equilibration Lag Time

Given the fact that equilibration rates do differ, is it possible to have a simple approach to lagging temperature and RH values? Based on our own data, on published data from Kodak concerning film,[57,58] on data from the Library of Congress concerning books,[59] and on other sources and experiences,[25] IPI feels that satisfactory accuracy can be obtained by means of an approximation that uses "moving averages" of temperature and RH for determining PI values. Instead of using the currently sensed room air temperature for looking up PI, the temperature for PI lookup should be derived from *the average of the previous 24 hours' temperature readings*.

A moving average means that the last 24 hours of temperature readings are kept in a table and are averaged together to obtain the temperature value used for looking up the current PI. When a new reading is made, the oldest reading is discarded and the newest is inserted into the table. This approach tends to "damp out" very short-term temperature fluctuations but still tracks temperature change closely. Because 24 hours is a time period during which even the largest objects would have time to reach equilibrium, and because all of the readings in the previous 24 hours influence the average, this approach seems to balance fairly well the varying rates of thermal equilibration for diverse collection materials. For the IPI "book-on-a-shelf" experiment, a 12-hour lag most closely matched actual behavior, but a 24-hour lag was also very close. To allow for more massive objects or groups of objects, a 24-hour lag was chosen for general use in looking up PI for use in TWPI calculations.

RH Equilibration Lag Time

A similar approximation strategy is used in lagging RH values, except that the time period over which the moving average is saved is much longer: 30 days instead of 24 hours. RH equilibration times range from minutes to months, but most often are measured in weeks, not hours. An everyday example would be the time necessary for "green" wood to dry out sufficiently for use as construction lumber or firewood. This is a moisture equilibration process that often takes three to six months or more. With RH, it is definitely the long-term average that counts, since full equilibration for a book or box of film takes several weeks at least, and sometimes much longer.[37] A 30-day moving average is a balanced approach that ignores short-term events without sacrificing their accumulated long-term effect. Therefore, in looking up PI values in the PI definition table, an average of the previous 24 hours of temperature data and 30 days of humidity data should be used, not the currently sensed temperature and RH. If less than 24 hours of temperature data exist, or less than 30 days of RH data exist, whatever data is available should be averaged together to obtain the temperature and RH for PI lookup.

References

[1] Donald K. Sebera, *Isoperms: An Environmental Management Tool*, (Washington, D.C.: The Commission on Preservation and Access, June 1994)

[2] Nancy E. Gwinn, "Politics and Practical Realities: Environmental Issues for the Library Administrator," in *Advances in Preservation and Access*, Barbara Bruckner Higginbotham and Mary E. Jackson, eds. (Westport, CT: Meckler Corporation, 1992) Vol. 1, pp. 135-146.

[3] Judith Stanley, "Buying Time: A Commentary on the Fiscal Realities of Implementing Library Preservation Programmes," *Libr. Ass. Rec.*, 93, 8:523-526 (August 1991).

[4] John H. Hammer, "On the Political Aspects of Book Preservation in the U.S.," in *Advances in Preservation and Access*, Barbara Bruckner Higginbotham and Mary E. Jackson, eds., Vol. 1 (Westport, CT: Meckler Corporation, 1992), pp. 22-40.

[5] P. Z. Adelstein, J. M. Reilly, D. W. Nishimura, and C. J. Erbland, "Stability of Cellulose Ester Base Photographic Film: Part I—Laboratory Testing Procedures," *Journal of Society of Motion Picture and Television Engineers*, 101, 5:336-346 (May 1992).

[6] P. Z. Adelstein, J. M. Reilly, D. W. Nishimura, and C. J. Erbland, "Stability of Cellulose Ester Base Photographic Film: Part II—Practical Storage Considerations," *Journal of Society of Motion Picture and Television Engineers*, 101, 5:347-353 (May 1992).

[7] John W. C. Van Bogart, *Magnetic Tape Storage and Handling: A Guide for Libraries and Archives*, (Washington, D.C.: The Commission on Preservation and Access and The National Media Laboratory, June 1995).

[8] Stefan Michalski, *A Systematic Approach to the Conservation (Care) of Museum Collections*, with technical appendices by Maureen MacDonald, Stefan Michalski, Thomas Strang, Jean Tetreault, and R. Scott Williams (Canadian Conservation Institute, May 1992).

[9] David Erhardt and Marion Mecklenburg, "Relative Humidity Re-examined," *Preventive Conservation Practice, Theory and Research*, Preprints of the Contributions to the Ottawa Congress, 12–16 September 1994, Ashok Roy and Perry Smith, eds., (London: The International Institute for Conservation of Historic and Artistic Works, 1994), pp. 32–38.

[10] G. Gray, "An Accelerated-Aging Study Comparing Kinetic Rates vs. TAPPI Standard 543," *Journal of TAPPI*, 52:325-334 (1969).

[11] G. Gray, "Determination and Significance of Activation Energy in Permanence Tests," *Preservation of Paper and Textiles of Historic and Artistic Value*, J. C. Williams, ed., Advances in Chemistry Series, 164 (Washington, D. C.: American Chemical Society, 1977).

[12] B. L. Browning and W. A. Wink, "Studies on the Permanence and Durability of Paper, 1 Prediction of Paper Permanence," *TAPPI*, 51:156 (1968).

[13] Edward F. Cuddihy, "Kinetics of the Humid Aging of Magnetic Recording Tape," *IEEE Transactions on Magnetics*, 18, 5:993-999 (1982).

[14] D. W. Brown, R. E. Lowery and L. E. Smith, "Prediction of the Long Term Stability of Polyester-Based Recording Media," NBSIR-83/2750, (Gaithersburg, MD: U.S. National Institute of Standards and Technology, August 1983).

[15] P. Z. Adelstein and J. L. McCrea, "Stability of Processed Polyester Base Photographic Films," *Journal of Applied Photographic Engineering*, 7:160-167 (December 1981).

[16] M. Edge, N. S. Allen, T. S. Jewitt, and C. V. Horie, "Fundamental Aspects of the Degradation of Cellulose Triacetate Base Cinematograph Film," *Polymer Degradation and Stability*, 25:345-362 (1989).

[17] D. K. Sebera, "A Graphical Representation of the Relationship of Environmental Conditions to the Permanence of Hygroscopic Materials and Composites," *Proceedings of the International Symposium: Conservation in Archives* (National Archives of Canada in conjunction with the International Council on Archives, 1988), pp. 51-75.

[18] *Electronic Environmental Monitoring in Museums*, Robert Child, ed., Conservation Monograph Series (Clwyd, Wales: Archetype Publications, 1993).

[19] Stefan Michalski, "Relative Humidity: A Discussion of Correct/Incorrect Values," preprint, 10th Triennial Meeting of ICOM Committee for Conservation (August 1993).

[20] David Erhardt, Marion F. Mecklenburg, Charles S. Tumosa, and Mark McCormick-Goodhart, "The Determination of Allowable RH Fluctuations," *WAAC Newsletter*, 17:19–23 (January 1995).

[21] Mark McCormick-Goodhart and Marion F. Mecklenburg, "Cold Storage Environments for Photographic Materials," *Final Program—Advance Printing of Paper Summaries*, IS&T 46th Annual Conference, Boston (Springfield, VA: IS&T, 1993), pp. 277-280.

[22] Garry Thomson, *The Museum Environment*, 2nd ed. (London: Butterworth-Heinemann Ltd., 1986).

[23] William P. Lull and Paul N. Banks, *Conservation Environment Guidelines for Libraries and Archives in New York State*, Report sponsored by New York State Program for the Conservation and Preservation of Library Research Materials at the New York State Library (New York State Library, September 1990).

[24] M. McCormick-Goodhart and M. Mecklenburg, "Cold Storage Environments for Photographic Materials." Internal report of the Conservation Analytical Laboratory, Smithsonian Institution, 1992. Also in *Topics in Photographic Conservation #5*, (Photographic Materials Group of the AIC, June 1993).

[25] V. Daniel and S. Maekawa, *Hygrometric Half-Lives of Museum Cases* (The Getty Conservation Institute, 1991). Also, V. Daniel and S. Maekawa, "The Moisture Buffering Capability of Museum Cases," *Materials Research Society Symposium Proceedings*, 267:453-458 (1992).

[26] C. C. Bard, G. W. Larson, H. A. Hammond, and C. Packard, "Predicting Long-Term Dark Storage Dye Stability Characteristics of Color Photographic Products from Short-Term Tests," *Journal of Applied Photographic Engineering*, 6, 2:42-45 (1980).

[27] P. Z. Adelstein, C. L. Graham, and L. E. West, "Preservation of Motion Picture Color Films Having Permanent Value," *Journal of the Society of Motion Picture and Television Engineers*, 79, 11:1011-1018 (November 1970).

[28] *Stability of Color Photographic Images—Methods for Measuring*, ANSI Standard IT9.9-1990 (New York: American National Standards Institute, 1991).

[29] D. F. Kopperl, R. J. Anderson, R. Codori, R. Ellison, and B. V. Erbland, "Quality Improvements and Control Procedures at the Image Stability Technical Center," *Journal of Imaging Technology*, 16:198–202 (October 1990).

[30] Image Permanence Institute, "Report of Contract Tests: Image Stability of Commercial Color Papers," unpublished report (Rochester, NY: 1989).

[31] Douglas W. Nishimura, *Color Microfilm Dark Stability Research*, Final Report to the Commission on Preservation and Access (August 1992).

[32] J. M. Reilly, P. Z. Adelstein, and D. W. Nishimura, *Preservation of Safety Film*, Final Report to the Office of Preservation, National Endowment for the Humanities, NEH Grant # PS-20159-88 (Rochester, NY: Image Permanence Institute, March 1991).

[53] James M. Reilly, Peter Z. Adelstein, Douglas W. Nishimura, and Catherine J. Erbland, *New Approaches to Safety Film Preservation*, Final Report to National Endowment for the Humanities, NEH Grant # PS-20445-91 (April 1994).

[54] *Conservation of Photographs*, Kodak Publication No. F-40 (Rochester, NY: Eastman Kodak Company, 1985).

[55] James M. Reilly, *The IPI Storage Guide for Acetate Film*, (Rochester, NY: Image Permanence Institute, 1993).

[56] Image Permanence Institute, unpublished data from research project on deterioration of color photographic dyes, to be published in 1996 by the New York State Program for the Conservation and Preservation of Library Research Materials.

[57] *Physical Properties of Kodak Aerial Films*, Kodak Publication M-62 (Rochester, NY: Eastman Kodak Company, 1972), pp. 5-6.

[58] *Physical and Chemical Behavior of Kodak Aerial Films*, Kodak Publication M-63 (Rochester, NY: Eastman Kodak Company, 1974), pp. 17-20.

[59] Chandru J. Shahani, Frank H. Hengemihle, and Norman Weberg, "Options in Preservation of Library and Archive Collections," presented at the National Library of India (December 1990).

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